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Interspecies interactions between *Microcystis aeruginosa* PCC 7806 and *Desmodesmus subspicatus* SAG 86.81 in a co-cultivation system at various growth phases

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ABSTRACT

In lakes, cyanobacterial blooms are frequently associated with green algae and dominate the phytoplankton community in successive waves. In the present study, the interactions between *Microcystis aeruginosa* PCC 7806 and *Desmodesmus subspicatus* were studied to clarify the probable ecological significance of algal secondary metabolites; focusing on the role of cyanotoxin 'microcystin-LR' (MC-LR). A dialysis co-cultivation technique was applied where *M. aeruginosa* was grown inside and *D. subspicatus* was cultured outside of the dialysis tubing. The concentration of the intra- and extracellular MC-LR and the growth of two species were measured at different time points over a period of one month. Additionally, the growth of the two species in the culture filtrate of one another and the effect of the purified MC-LR on the growth of the green alga were studied. The results indicated that the co-existing species could affect each other depending on the growth phases. Despite the early dominance of *D. subspicatus* during the logarithmic phase, *M. aeruginosa* suppressed the growth of the green alga at the stationary phase, which coincided with increased MC production and release. However, the inhibitory effects of *Microcystis* might be related to its other extracellular metabolites rather than, or possibly in addition to, MC.

1. Introduction

Monitoring the composition of the phytoplankton populations has shown that algal species undergo a sequence of dominance; a phenomenon called seasonal succession (Reynolds, 1980). According to the seasonal pattern, diatoms (Diatomophyceae) dominate the phytoplankton community during the winter and spring, whereas during the summer green algae (Chlorophyceae) prevail, and in the late summer and autumn cyanobacteria outcompete their predecessors (Sommer, 1989). However, under environmental parameters favouring algal growth such as high nutrient availability (primarily nitrogen and phosphorous) in eutrophic waters, abundant sunlight, warm water temperature (>25 °C), and stagnant water, some species of cyanobacteria grow explosively and form large blooms outside of their typical season (Paerl and Otten, 2013; Rastogi et al., 2015; Scholz et al., 2017). Additionally, eutrophication of lakes and climate change influence the algal seasonal pattern, favouring the formation of harmful cyanobacterial blooms. The occurrence of toxic cyanobacterial blooms, which have undesirable effects on humans, animals, and aquatic biota, has been reported in many countries throughout the world (Zanchett and Oliveira-Filho, 2013; Svirčev et al., 2017).

Understanding the factors that induce the shift in the phytoplankton composition to the domination of a toxic bloom holds many advantages, especially concerning water quality, treatment, and governance. Recent studies reported that the seasonal fluctuation of phytoplankton species is influenced not only by the environmental factors (Chen et al., 2003; Karadžić et al., 2013; Yang et al., 2018) but also by the interspecies interactions (Sukenik et al., 2002; Vardi et al., 2002; Legrand et al., 2003; Leão et al., 2009; Chia et al., 2018). In freshwater ecosystems, cyanobacterial blooms influence the composition of microbial communities and the co-occurrence patterns of eukaryotic plankton (Xue et al., 2018; L. Liu et al., 2019; M. Liu et al., 2019).

Abbreviations: MCs, Microcystins; MeOH, Methanol; TFA, Trifluoroacetic acid; ACN, Acetonitrile

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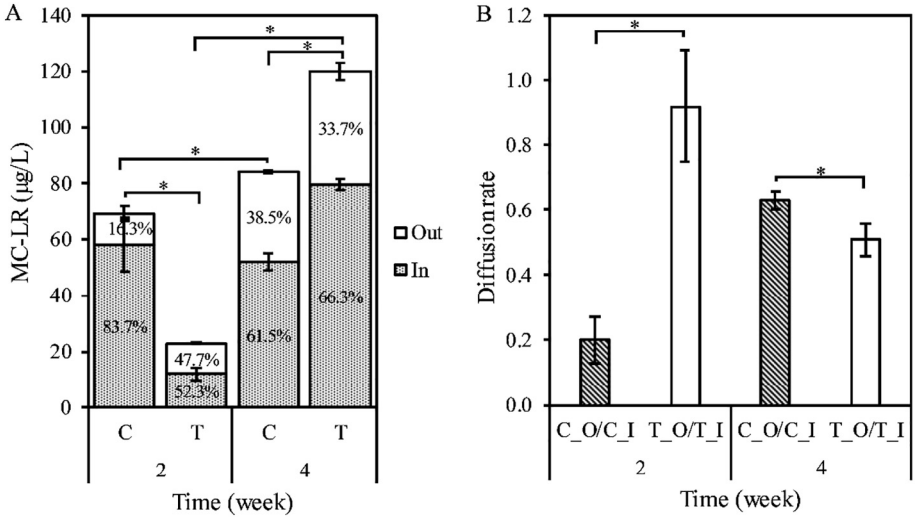

Fig. 7. The percentage (A) and the diffusion rate (B) of the extracellular MC-LR in mono and co-cultures at the 2nd and 4th week (C: control, T: treatment, I: inner membrane O: outer membrane). Data represent mean values ± standard deviation (n = 3). Significant differences observed at $p < 0.05$ (*).

The results indicated that in the co-cultivation system, both species affected one another depending on the growth stages. At the early logarithmic phase of growth, the presence of *Microcystis* did not influence the growth of green alga, while the green alga started to outcompete the co-cultured *Microcystis* which was further inhibited during the exponential phase of growth. The inhibitory effects of the green algae and some species of cyanobacteria on the growth, MC production and photosynthesis of *Microcystis* spp. was reported in other investigations through the reduction in chlorophyll *a* content (Jia et al., 2008), the production of bioactive compounds capable of inhibition of MC production and increasing of the activity of alkaline phosphatase (ALP) (Rzymski et al., 2014), disturbing of the synthesis of proteins and polysaccharides and chlorophyll *a* content (Qiu et al., 2019), induction of cell lysis (Harel et al., 2013; Bittencourt-Oliveira et al., 2015), and the greater nutrient uptake ability of the green algae (Huan et al., 2006). Moreover, the results indicated that the reduction rate of MC release in co-cultures was at the same level as the decreased rate of the biomass of *Microcystis*. Therefore, the reduction of the extracellular MC-LR was due to the decreased *M. aeruginosa* cell density, and the decreased total MC content have resulted from the significant suppression of the MC synthesis. Since the MC production rate is positively related to the cell division rate, it can be assumed that the growth inhibition and suppression of MC synthesis might be related to the limiting factors such as light intensity and interferences in the nutrient uptake capability of *Microcystis* (Orr and Jones, 1998; Lyck, 2004; Downing et al., 2005; Deblois and Juneau, 2010; Chaffin et al., 2018; Kramer et al., 2018). MC production is highly depended on the nitrogen supply (Harke and Gobler, 2013, 2015). The binding site of NtcA, a global nitrogen regulator in cyanobacteria, was found in the promoter region of the mcy gene cassette (Ginn et al., 2010).

On the other hand, the study by Huan et al. (2006) demonstrated that in a mixed culture, the growth of *M. aeruginosa* was inhibited due to the greater ability of the green alga *Chlorella ellipsoidea* in the utilisation of nitrogen and phosphorous. Zhang et al. (2013) found that the green algae *Quadrigula chodatii* FACHB-1080 inhibited the growth of *M. aeruginosa* PCC7820 through the production of allelochemicals such as dibutyl phthalate and beta-sitosterol, and the interferences in the nitrogen uptake and utilisation by *Microcystis*. In the current study, the culture filtrate of the green alga negatively affected the growth of *Microcystis*, which might reinforce the probable interferences of the extracellular metabolites of the green alga in out-competing of the co-existing *Microcystis*. Moreover, the inhibition of the growth of *Microcystis* was observed earlier in co-cultures (after the first week) than compared to exposure with the *Desmodesmus* filtrate, which might be due to the interferences of the green alga in nutrient uptake capability of *Microcystis* in co-cultures. However, it is important to point out that the MC production rate is regulated by light intensity (Deblois and Juneau, 2010; Renaud et al., 2011). *With the progression of the experiment,* light limitation may have occurred due to the *shading of the dense algal cultures, especially at the logarithmic phase of growth,* which should be considered in future studies.

Over time, towards the stationary phase of growth, in co-cultures, MC production and release were increased, coinciding with the inhibition of the growth of the green alga. However, the exposure of the green alga to the extracted MC-LR showed that the growth of green alga was inhibited only at MC concentrations that were greater than the outer membrane MC concentration (79.5 g/L) of the co-culture experiments. Past studies have shown that the exposure of aquatic organisms to the *Microcystis* crude extracts caused greater activity in detoxification enzymes in the target species, compared to the purified MCs and the intact cells of *Microcystis* due to the presence of the other toxin modulating factors (Pietsch et al., 2001; Vasconcelos et al., 2007; Scoglio, 2018). However, the interspecies interference between intact cells in a consistent mode of microbial exposure might be more complicated. On the other hand, regarding the inhibitory effects of the *Microcystis* spent medium on the growth of green alga, it might be assumed that the other probable extracellular metabolites of *Microcystis* might be involved in the interspecies interplay. *Microcystis* is known to produce the other secondary metabolites such as micropeptin, microviridin, microgenin, as well as some unknown compounds that might be involved in the interferences of cyanobacteria with other phytoplankton species (Ikawa et al., 1996; Reshef and Carmeli, 2001; Ploutno et al., 2002). However, the probable synergistic effects between other metabolites and MC-LR to outcompete the co-existing species should be considered.

Previous studies have shown that in a mixed culture, *M. aeruginosa* severely inhibited the growth of the green algae *Chlorella pyrenoidosa* (Hong et al., 2010), and the growth and photosynthesis of the dinoflagellate *Peridinium gatunense* through abolishing carbonic anhydrase activity (Sukenik et al., 2002). Furthermore, the growth and photosynthesis of other aquatic organisms which were exposed to the purified MCs (25–50 g/mL) or the crude extracts of *Microcystis*, were inhibited due to the reduction of CO_2 uptake, depletion of nitrogen fixation (Singh et al., 2001), and promotion of the oxidative stress (Pflugmacher, 2004; Paskerová et al., 2012). Therefore, at the exponential phase of growth, the growth of green alga was not altered,

perhaps due to the repair systems of the green alga such as anti-oxidative enzymes (Cirulis et al., 2013). The study by Mohamed (2008) showed that MCs had been absorbed and biotransformed in the green algae, *Chlorella* and *Scenedesmus*. Additionally, it is speculated that the green alga could produce intra- and extracellular polysaccharides as an adaptive response to protect the cells against the oxidative stress (Mohamed, 2008; El-Sheekh et al., 2012). However, by entering the stationary phase of growth, the increased release of metabolites from *Microcystis* due to the increased lysis of *Microcystis* cells might have resulted in the inhibition of the growth of the green alga through the interferences in the photosynthesis process, inhibition of serin protease activity and the induction of oxidative stress (Smith et al., 2008).

On the other hand, the results of the co-cultivation experiments indicated that the rate of enhanced toxin release in co-cultures was significantly higher than the elevated rate of cell density. While in monocultures, they have enhanced approximately at the same level. Previous studies showed that the MC production and release could be induced under stress conditions such as the limited nutrient availability caused by the presence of the competitor species (Kaplan et al., 2012; Pimentel and Giani, 2014; Yeung et al., 2016). Additionally, the extracellular metabolites of green algae could induce MC production in *M. aeruginosa* (Bittencourt-Oliveira et al., 2015), and cause disruption of *Microcystis* cell membrane at the stationary phase of growth (Harel et al., 2013).

In summary, applying a co-cultivation system allowed investigating the interspecies interference between intact cells in a consistent mode of microbial exposure to simulate the natural ecosystems where microorganisms are co-existing within various microbial communities. However, the natural ecosystems are much more complicated than the laboratory-controlled conditions. A combination of the conventional exposure of target species to cellular exudates, purified metabolites such as MCs and co-cultivation studies might provide more insights into the probable mechanisms of the interspecies interplays, through the resource competitions, the interferences of the bio-compounds, or a combination of both. Moreover, the characterisation of the probable bioactive compounds of the green alga might open the ways for the control of harmful cyanobacterial blooms or minimise the harmful effects of the release of a high concentration of MCs into the natural ecosystem that come into contact with the aquatic species following toxic cyanobacterial bloom degradation. With this in mind, it should be considered whether exudates of green alga are non-toxic to non-target organisms.

6. Conclusions

This study highlights the potential of the dialysis membrane to determine the interspecific interactions between the intact cells of the co-growing species. It can be used in future laboratory or field studies by the positioning of the dialysis membrane containing the individual species or the mixed samples in the natural ecosystems of the occurring cyanobacterial blooms.

It should be considered that the interspecies interactions through the bioactive compounds or due to the competition for the resources might influence the dynamics of the phytoplankton community. Both species might produce metabolites to influence the growth of each other negatively. The inhibition of the green alga at a concentration higher than the environmentally relevant concentrations of MCs (1–10 g/L) might explain the co-existence of the cyanobacteria and green algae in the phytoplankton community. MC might improve the fitness of *Microcysts* cells under the stress conditions induced by the presence of the green alga. However, the inhibitory effects of *Microcystis* might be related to other probable extracellular metabolites of *Microcystis* in addition to MC. The presence of MC may reinforce the inhibitory effects of the *Microcystis* on the growth of the co-existing green alga which should be considered in future studies.

Data availability

All data reported in the present study are available via the Supplemental Data files or by request from the authors (stephan.pflugmacher@helsinki.fi).

Declaration of Competing Interest

None.

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References

Bittencourt-Oliveira, M., Chia, M.A., De Oliveira, H.S.B., Araújo, M.K.C., Molica, R.J.R., Dias, C.T.S., 2015. Allelopathic interactions between microcystin-producing and non-microcystin-producing cyanobacteria and green microalgae: implications for microcystins production. J. Appl. Phycol. 27, 275–284.

Chaffin, J.D., Davis, T.W., Smith, D.J., Baer, M.M., Dick, G.J., 2018. Interactions between nitrogen form, loading rate, and light intensity on *Microcystis* and *Planktothrix* growth and microcystin production. Harmful Algae 73, 84–97.

Chen, Y., Qin, B., Teubner, K., Dokulil, M.T., 2003. Long-term dynamics of phytoplankton assemblages: *Microcystis*-domination in Lake Taihu, a large shallow lake in China. J. Plankton Res. 25, 445–453.

Chia, M.A., Jankowiak, J.G., Kramer, B.J., Goleski, J.A., Huang, I.-S., Zimba, P.V., do Carmo Bittencourt-Oliveira, M., Gobler, C.J., 2018. Succession and toxicity of *Microcystis* and *Anabaena* (*Dolichospermum*) blooms are controlled by nutrient-dependent allelopathic interactions. Harmful Algae 74, 67–77.

Cirulis, J.T., Scott, J.A., Ross, G.M., 2013. Management of oxidative stress by microalgae. Can. J. Physiol. Pharmacol. 91, 15–21.

Deblois, C.P., Juneau, P., 2010. Relationship between photosynthetic processes and microcystin in *Microcystis aeruginosa* grown under different photon irradiances. Harmful Algae 9, 18–24.

Downing, T., Meyer, C., Gehringer, M., Van de Venter, M., 2005. Microcystin content of *Microcystis aeruginosa* is modulated by nitrogen uptake rate relative to specific growth rate or carbon fixation rate. Environ. Toxicol. 20, 257–262.

Dunker, S., Jakob, T., Wilhelm, C., 2013. Contrasting effects of the cyanobacterium *Microcystis aeruginosa* on the growth and physiology of two green algae, *Oocystis marsonii* and *Scenedesmus obliquus*, revealed by flow cytometry. Freshw. Biol. 58, 1573–1587.

El-Sheekh, M.M., Khairy, H.M., El-Shenody, R., 2012. Algal production of extra and intracellular polysaccharides as an adaptive response to the toxin crude extract of *Microcystis aeruginosa*. Iran. J. Environ. Health Sci. Eng. 9, 10.

Ginn, H., Pearson, L., Neilan, B., 2010. NtcA from *Microcystis aeruginosa* PCC 7806 is autoregulatory and binds to the microcystin promoter. Appl. Environ. Microbiol. 76, 4362–4368.

Harel, M., Weiss, G., Lieman-Hurwitz, J., Gun, J., Lev, O., Lebendiker, M., Temper, V., Block, C., Sukenik, A., Zohary, T., Braun, S., Carmeli, S., Kaplan, A., 2013. Interactions between *Scenedesmus* and *Microcystis* may be used to clarify the role of secondary metabolites. Environ. Microbiol. Rep. 5, 97–104.

Harke, M.J., Gobler, C.J., 2013. Global transcriptional responses of the toxic cyanobacterium, *Microcystis aeruginosa*, to nitrogen stress, phosphorus stress, and growth on organic matter. PLoS One 8, e69834.

Harke, M.J., Gobler, C.J., 2015. Daily transcriptome changes reveal the role of nitrogen in controlling microcystin synthesis and nutrient transport in the toxic cyanobacterium, *Microcystis aeruginosa*. BMC Genomics 16, 1068.

Hong, Y., Zou, D., Xiao, Q., Zhang, Z., Hu, H., 2010. Interactive Relationships of *Microcystis aeruginosa* and Three Species of *Chlorella* Under the Condition of Coexistence. International Conference on Environmental Engineering and Applications (ICEEA). IEEE, Singapore.

Huan, H.-l., Wang, Y.-y., Han, L., Li, J.-h., 2006. Inhibiting effect of *Chlorella ellipsoidea* on growth of *Microcystis aeruginosa* through competing for nutrients. J. Ecol. Rural Environ. 3, 29–32.

Ikawa, M., Haney, J.F., Sasner, J.J., 1996. Inhibition of *Chlorella* growth by the lipids of cyanobacterium *Microcystis aeruginosa*. Hydrobiologia 331, 167–170.

Jia, X.H., Shi, D.J., Kang, R.J., Li, H.M., Liu, Y., An, Z.Z., Wang, S.S., Song, D.H., Du, G.S., 2008. Allelopathic inhibition by *Scenedesmus obliquus* of photosynthesis and growth of *Microcystis aeruginosa*. In: Allen, J.F., Gantt, E., Golbeck, J.H., Osmond, B. (Eds.), Photosynthesis. Energy From the Sun. 14th International Congress on Photosynthesis. Springer, The Netherlands, pp. 1339–1342.

Kaplan, A., Harel, M., Kaplan-Levy, R.N., Hadas, O., Sukenik, A., Dittmann, E., 2012. The languages spoken in the water body (or the biological role of cyanobacterial toxins). Front. Microbiol. 3, 1–11.

Karadžić, V., Simić, G.S., Natić, D., Ržaničanin, A., Ćirić, M., Gačić, Z., 2013. Changes in the phytoplankton community and dominance of *Cylindrospermopsis raciborskii* (Wolosz.) Subba Raju in a temperate lowland river (Ponjavica, Serbia).

Hydrobiologia 711, 43–60.
Kramer, B.J., Davis, T.W., Meyer, K.A., Rosen, B.H., Goleski, J.A., Dick, G.J., Oh, G., Gobler, C.J., 2018. Nitrogen limitation, toxin synthesis potential, and toxicity of cyanobacterial populations in Lake Okeechobee and the St. Lucie River Estuary, Florida, during the 2016 state of emergency event. PLoS One 13, e0196278.
Leão, P.N., Vasconcelos, M.T.S., Vasconcelos, V.M., 2009. Allelopathy in freshwater cyanobacteria. Crit. Rev. Microbiol. 35, 271–282.
Leflaive, J., Ten-Hage, L., 2007. Algal and cyanobacterial secondary metabolites in freshwaters: a comparison of allelopathic compounds and toxins. Freshw. Biol. 52, 199–214.
Legrand, C., Rengefors, K., Fistarol, G.O., Graneli, E., 2003. Allelopathy in phytoplankton-biochemical, ecological and evolutionary aspects. Phycologia 42, 406–419.
Li, Y., Li, D., 2012. Competition between toxic *Microcystis aeruginosa* and nontoxic *Microcystis wesenbergii* with *Anabaena* PCC7120. J. Appl. Phycol. 24, 69–78.
Liu, L., Chen, H., Liu, M., Yang, J.R., Xiao, P., Wilkinson, D.M., Yang, J., 2019. Response of the eukaryotic plankton community to the cyanobacterial biomass cycle over 6 years in two subtropical reservoirs. ISME J. https://doi.org/10.1038/s41396-019-0417-9. in press.
Liu, M., Liu, L., Chen, H., Yu, Z., Yang, J.R., Xue, Y., Huang, B., Yang, J., 2019. Community dynamics of free-living and particle-attached bacteria following a reservoir *Microcystis* bloom. Sci. Total Environ. 660, 501–511.
Lyck, S., 2004. Simultaneous changes in cell quotas of microcystin, chlorophyll a, protein and carbohydrate during different growth phases of a batch culture experiment with *Microcystis aeruginosa*. J. Plankton Res. 26, 727–736.
Mohamed, Z.A., 2008. Polysaccharides as a protective response against microcystin-induced oxidative stress in *Chlorella vulgaris* and *Scenedesmus quadricauda* and their possible significance in the aquatic ecosystem. Ecotoxicology 17, 504–516.
Nishizawa, T., Ueda, A., Asayama, M., Fujii, K., Harada, K.I., Ochi, K., Shirai, M., 2000. Polyketide synthase gene coupled to the peptide synthetase module involved in the biosynthesis of the cyclic heptapeptide microcystin. J. Biochem. 127, 779–789.
Omidi, A., Esterhuizen-Londt, M., Pflugmacher, S., 2017. Still challenging: the ecological function of the cyanobacterial toxin microcystin–what we know so far. Toxin Rev. 37, 87–105.
Orr, P.T., Jones, G.J., 1998. Relationship between microcystin production and cell division rates in nitrogen-limited *Microcystis aeruginosa* cultures. Limnol. Oceanogr. 43, 1604–1614.
Paerl, H.W., Otten, T.G., 2013. Harmful cyanobacterial blooms: causes, consequences, and controls. Microb. Ecol. 65, 995–1010.
Paskerová, H., Hilscherová, K., Bláha, L., 2012. Oxidative stress and detoxification biomarker responses in aquatic freshwater vertebrates exposed to microcystins and cyanobacterial biomass. Environ. Sci. Pollut. Res. 19, 2024–2037.
Pflugmacher, S., 2004. Promotion of oxidative stress in the aquatic macrophyte *Ceratophyllum demersum* during biotransformation of the cyanobacterial toxin microcystin-LR. Aquat. Toxicol. 70, 169–178.
Pietsch, C., Wiegand, C., Amé, M.V., Nicklisch, A., Wunderlin, D., Pflugmacher, S., 2001. The effects of a cyanobacterial crude extract on different aquatic organisms: evidence for cyanobacterial toxin modulating factors. Environ. Toxicol. 16, 535–542.
Pimentel, J.S., Giani, A., 2014. Microcystin production and regulation under nutrient stress conditions in toxic *Microcystis* strains. Appl. Environ. Microbiol. 80, 5836–5843.
Ploutno, A., Shoshan, M., Carmeli, S., 2002. Three novel protease inhibitors from a natural bloom of the cyanobacterium *Microcystis aeruginosa*. J. Nat. Prod. 65, 973–978.
Qiu, Y., Wang, Z., Liu, F., Liu, J., Tan, K., Ji, R., 2019. Inhibition of *Scenedesmus quadricauda* on *Microcystis os-aquae*. Appl. Microbiol. Biotechnol. 1–10.
Rastogi, R.P., Madamwar, D., Incharoensakdi, A., 2015. Bloom dynamics of cyanobacteria and their toxins: environmental health impacts and mitigation strategies. Front. Microbiol. 6, 1254.
Renaud, S.L., Pick, F.R., Fortin, N., 2011. The effect of light intensity on the relative dominance of toxigenic and nontoxigenic strains of *Microcystis aeruginosa*. Appl. Environ. Microbiol. 77, 7016–7022.
Reshef, V., Carmeli, S., 2001. Protease inhibitors from a water bloom of the cyanobacterium *Microcystis aeruginosa*. Tetrahedron 57, 2885–2894.
Reynolds, C.S., 1980. Phytoplankton assemblages and their periodicity in stratifying lake systems. Ecography 3, 141–159.
Rippka, R., Deruelles, J., Waterbury, J.B., Herdman, M., Stanier, R.Y., 1979. Generic assignments, strain histories and properties of pure cultures of cyanobacteria. Microbiology 111, 1–61.
Rzymski, P., Poniedziałek, B., Kokociński, M., Jurczak, T., Lipski, D., Wiktorowicz, K., 2014. Interspecific allelopathy in cyanobacteria: Cylindrospermopsin and *Cylindrospermopsis raciborskii* effect on the growth and metabolism of *Microcystis aeruginosa*. Harmful Algae 35, 1–8.
Scholz, S.N., Esterhuizen-Londt, M., Pflugmacher, S., 2017. Rise of toxic cyanobacterial blooms in temperate freshwater lakes: causes, correlations and possible countermeasures. Toxicol. Environ. Chem. 99, 543–577.
Scoglio, S., 2018. Microcystins in water and in microalgae: do microcystins as microalgae contaminants warrant the current public alarm? Toxicol. Rep. 5, 785–792.
Sedmak, B., Kosi, G., 1998. The role of microcystins in heavy cyanobacterial bloom formation. J. Plankton Res. 20, 691–708.
Singh, D.P., Tyagi, M., Kumar, A., Thakur, J., Kumar, A., 2001. Antialgal activity of a hepatotoxin-producing cyanobacterium, *Microcystis aeruginosa*. World J. Microbiol. Biotechnol. 17, 15–22.
Sivonen, K., 2009. Cyanobacterial toxins. In: Schaechter, M. (Ed.), Encyclopedia of Microbiology. Elsevier, The Netherlands, pp. 290–307.
Smith, J.L., Boyer, G.L., Zimba, P.V., 2008. A review of cyanobacterial odorous and bioactive metabolites: impacts and management alternatives in aquaculture. Aquaculture 280, 5–20.
Sommer, U., 1989. Plankton Ecology: Succession in Plankton Communities. Springer-Verlag, Berlin.
Sukenik, A., Eshkol, R., Livne, A., Hadas, O., Rom, M., Tchernov, D., Vardi, A., Kaplan, A., 2002. Inhibition of growth and photosynthesis of the dinoflagellate *Peridinium gatunense* by *Microcystis* sp.(cyanobacteria): a novel allelopathic mechanism. Limnol. Oceanogr. 47, 1656–1663.
Svirčev, Z., Drobac, D., Tokodi, N., Mijović, B., Codd, G.A., Meriluoto, J., 2017. Toxicology of microcystins with reference to cases of human intoxications and epidemiological investigations of exposures to cyanobacteria and cyanotoxins. Arch. Toxicol. 91, 621–650.
Vardi, A., Schatz, D., Beeri, K., Motro, U., Sukenik, A., Levine, A., Kaplan, A., 2002. Dinoflagellate-cyanobacterium communication may determine the composition of phytoplankton assemblage in a mesotrophic lake. Curr. Biol. 12, 1767–1772.
Vasconcelos, V.M., Wiegand, C., Pflugmacher, S., 2007. Dynamics of glutathione-S-transferases in *Mytilus galloprovincialis* exposed to toxic *Microcystis aeruginosa* cells, extracts and pure toxins. Toxicon 50, 740–745.
Xue, Y., Chen, H., Yang, J.R., Liu, M., Huang, B., Yang, J., 2018. Distinct patterns and processes of abundant and rare eukaryotic plankton communities following a reservoir cyanobacterial bloom. ISME J. 12, 2263–2277.
Yang, J., Deng, X., Xian, Q., Qian, X., Li, A., 2014. Allelopathic effect of *Microcystis aeruginosa* on *Microcystis wesenbergii:* microcystin-LR as a potential allelochemical. Hydrobiologia 727, 65–73.
Yang, J., Tang, H., Zhang, X., Zhu, X., Huang, Y., Yang, Z., 2018. High temperature and pH favor *Microcystis aeruginosa* to outcompete *Scenedesmus obliquus*. Environ. Sci. Pollut. Res. 25, 4794–4802.
Yeung, A.C., D'Agostino, P.M., Poljak, A., McDonald, J., Bligh, M.W., Waite, T.D., Neilan, B.A., 2016. Physiological and proteomic responses of continuous cultures of *Microcystis aeruginosa* PCC 7806 to changes in iron bioavailability and growth rate. Appl. Environ. Microbiol. 82, 5918–5929.
Zanchett, G., Oliveira-Filho, E.C., 2013. Cyanobacteria and cyanotoxins: from impacts on aquatic ecosystems and human health to anticarcinogenic effects. Toxins 5, 1896–1917.
Zhang, P., Zhai, C., Wang, X., Liu, C., Jiang, J., Xue, Y., 2013. Growth competition between *Microcystis aeruginosa* and *Quadrigula chodatii* under controlled conditions. J. Appl. Phycol. 25, 555–565.